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Techno-economic comparisons of hydrogen and synthetic fuel production using forest residue feedstock

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ABSTRACT

Mobile distributed pyrolysis facilities have been proposed for delivery of a forest residue resource to bio-fuel facilities. This study examines the costs of producing hydrogen or synthetic petrol (gasoline) and diesel from feedstock produced by mobile facilities (bio-oil, bio-slurry, torrefied wood). Results show that using these feedstock can provide fuels at costs competitive to conventional bio-fuel production methods using gasification of a woodchip feedstock. Using a bio-oil feedstock in combination with bio-oil steam reforming or bio-oil upgrading can produce hydrogen or petrol and diesel at costs of 3.25 \$ kg^{-1} or 0.86 \$ $litre^{-1}$, respectively, for optimally sized bio-fuel facilities. When compared on an energy basis (\$ GJ^{-1}), hydrogen production costs tend to be lower than those for synthetic petrol or diesel production across a variety of bio-fuel production pathways.

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Introduction

Climate change concerns and government policies aimed at reducing greenhouse gas emissions from fossil fuels continue to contribute to an increasing demand for fuels from biomass sources ('bio-fuels'). The extent to which bio-fuels mitigate climate change by reducing greenhouse gas emissions compared against fossil fuels is a subject of debate, particularly when land use changes are considered in lifecycle analyses [1–5]. However, bio-fuels produced from waste wood, such as forest or mill residues, can reduce net carbon emissions whilst avoiding controversy related to land use change as they are a by-product of the forest industry [6].

Forest residues, in particular, have potential for increased utilisation for bio-fuel production – at present, most are burned on-site at the end of commercial forestry operations. However, forest residues suffer from low spatial and energy densities, which hinder their use as a biomass resource. Typically, forest residues are spread-out over wide areas of land, thus large distances are travelled for collection and delivery to bio-fuel production facilities. If forest residues are transported in their raw form or as woodchips, truck capacity is limited by volume rather than weight and, as a result, more delivery trips are required than if the truck were transporting a more energy dense substance at full weight capacity [7]. The combination of low spatial and energy densities of biomass results in high transport costs which, in turn, elevate the final bio-fuel production cost.

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One proposed method of reducing the cost of delivering a forest residue resource is to implement a distributed network of mobile biomass conversion facilities ('mobile facilities') near the location of forest residues [8,9]. These mobile facilities convert raw biomass to a more energy dense substance, which is then transported longer distances to a centralised bio-fuel production facility. Mobile facilities can be moved from a depleted region and relocated to a region with abundant forest residues. Relocating mobile facilities reduces transport distances of raw biomass material.

Two processes that are suited for mobile facilities are fast pyrolysis and torrefaction [10–12]. These are both forms of pyrolysis, which is the thermal decomposition of materials in the absence of oxygen. Fast pyrolysis involves high heating rates and short reaction times, and produces three main products: bio-oil, bio-char and syngas [13]. Transportable products from fast pyrolysis reactions are bio-oil or bio-slurry (a mixture of bio-oil and bio-char). Torrefaction occurs at lower temperatures than fast pyrolysis and the principal product suitable for transport is a solid char-like substance known as torrefied wood [14,15]. The energy and mass densities of the liquid and solid products are typically higher than those of forest residues or woodchips.

Upon delivery to a bio-fuel facility, the product of mobile facilities (bio-oil, bio-slurry or torrefied wood) can be used directly as feedstock for bio-fuel production. All products are suited for gasification [13,16], which produces syngas. This can be used to yield additional hydrogen via water gas shift reactions or to synthesise petrol (gasoline) and diesel via Fischer–Tropsch reactions. Alternatively, the bio-oil product of fast pyrolysis can undergo steam reforming to produce hydrogen or be upgraded to produce petrol and diesel. Therefore, implementing mobile facilities introduces new pathways for bio-fuel production using a forest residue resource.

Previous work by Brown et al. (2013) [9] studies forest residue feedstock delivery costs when using distributed mobile facilities. Results show that mobile torrefaction facilities can reduce the levelised delivered cost of feedstock ($ GJ^{-1}) compared to conventional woodchip delivery when transport distances are large (over 300 km) or when annual feedstock requirements are high (over 2.5 million m^3 per year). Bio-slurry product from mobile fast pyrolysis facilities can provide lower delivered feedstock costs than woodchips, but is more expensive than torrefied wood. Bio-oil product is the most expensive method of delivering a forest residue resource and is not cheaper than woodchip delivery for transport distances up to 500 km.

This study extends the work by Brown et al. (2013) [9] to examine the levelised cost of producing hydrogen or synthetic petrol and diesel in conjunction with a network of mobile facilities to harvest a forest residue resource. Previous studies have provided techno-economic evaluations of centralised and distributed bio-fuel facilities utilising forest residue resources and pyrolysis products e.g. Refs. [17–21], however no studies have been identified in the literature that consider the use of mobile facilities as a method of delivering a forest residue resource for similar analyses. An overview of the fuel production routes analysed in this study are shown in Fig. 1.

Gasification

Gasification is the conversion of carbon-based feedstock into large quantities of gaseous product and small amounts of char and ash [22]. It requires high temperatures between 500 and 1400 °C, and may be performed at pressures of 0.1–3.3 MPa [23]. The produced gas is cleaned to remove particulates, tars, alkali compounds, sulphur compounds, nitrogen compounds and other contaminants to yield a clean syngas consisting of carbon monoxide, hydrogen, carbon dioxide, water, and methane [24].

Syngas is a 'platform chemical' that can be used for many different purposes, including hydrogen production via the water gas shift and Fischer–Tropsch synthesis of petrol and diesel fuels [25]. Principal reactions that occur during gasification to produce syngas are outlined in Equations (1–7) (using methane as an example) [26]:

Reforming:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \tag{2}$$

Combustion:

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2 \tag{3}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4}$$

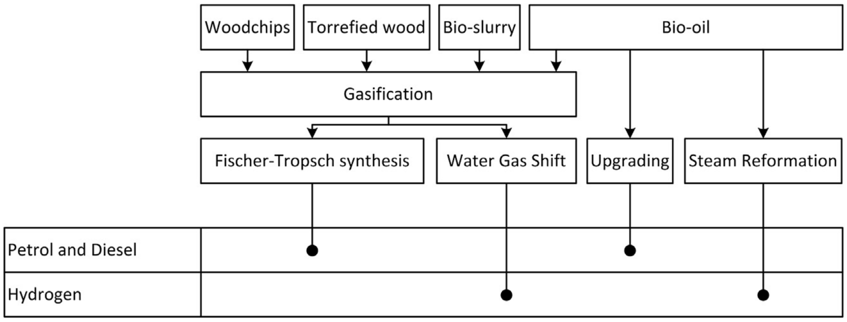

Fig. 1 – Bio-fuel production routes considered in this study using products of mobile facilities.

Water gas shift:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (5)$$

Carbon:

$$CH_4 \rightarrow C + 2H_2 \quad (6)$$

$$2CO \rightarrow C + CO_2 \quad (7)$$

Reforming reactions (Equations (1 and 2)) are endothermic and require input energy provided by concurrent exothermic reactions of partial oxidation (Equation (3)) or complete combustion (Equation (4)). The water gas shift reaction (Equation (5)) is mildly exothermic, and can assist in producing a hydrogen rich syngas under particular reactor conditions. Carbon is also produced during gasification (Equations (6 and 7)).

The three main types of gasification processes are fixed bed, fluidized bed and entrained flow gasifiers [27]. Gasification is an endothermic process and heat may be provided directly (by combustion of the gasification mixture) or indirectly (from an external source – usually a hot solid such as sand or olivine circulating between the gasifier and the char combustor). Each type of gasification process may use steam, air and/or oxygen as a gasification agent to promote conversion. Direct gasification usually uses high pressure air or oxygen, and indirect gasification typically uses steam [27].

This study is based on an entrained flow indirectly heated gasification process designed by Battelle Columbus Laboratory (BCL), commercially known as Silvagas. This gasification process is selected as it is applicable to, and has been studied for, biomass feeds and technical and cost information for the process exists in the literature [28,29]. The Silvagas process uses hot sand fluidised by steam to indirectly heat the carbonaceous feedstock to provide the thermal energy required for gasification [23]. The hot sand and char are separated from the gaseous stream into a char combustor where the sand is re-heated and re-circulated back into the gasification reactor. This gasification process produces high quality syngas with minimal nitrogen content [23].

Gasification of bio-oil, bio-slurry or torrefied wood requires a similar process to that of woodchip gasification [30–32]. Feeding liquid into a gasification reactor is typically easier than using a feed-hopper technique often used for woodchip feeds [13], and is an advantage of bio-oil and bio-slurry feeds. In addition, syngas quality is likely to be superior from gasification of bio-oil as many metals and minerals found in raw biomass, which can cause catalyst performance issues, are deposited in the char produced by fast pyrolysis reactions [33]. Gasification of torrefied wood is also found to produce improved syngas quality due to the lower moisture content of torrefied wood [32].

Water gas shift reaction

Syngas produced from gasification can undergo water gas shift reactions (Equation (5)) to increase the concentration of hydrogen in the syngas. The water gas shift combines carbon monoxide and water to form hydrogen and carbon dioxide. It is usually performed in two steps – a high temperature water gas shift (300–450 °C) and a low temperature water gas shift (200 °C) [34]. Once the syngas has been subject to water gas shift reactions, it is purified to yield hydrogen gas. Typical yields of hydrogen from gasification and water gas shift reactions are between 70 and 80 kgH_2 per tonne of biomass feed [27].

Fischer–Tropsch reactions

Synthetic hydrocarbon fuels can be produced from syngas via Fischer–Tropsch synthesis reactions. Pressures of 2–4 MPa are required, and different products are produced when reactions occur at different temperatures [28]. Low temperature synthesis (180–250 °C) produces primarily waxes and diesel, and high temperature synthesis (300–350 °C) produces alkenes and petrol [28]. The fuel mixture that is produced requires distillation to separate out petrol and diesel products.

The stoichiometry of all FT reactions can be represented using two basic reaction equations to describe the production of alkanes (Equation (8)) and alkenes (Equation (9)) [35]:

$$nCO + (2n + 1)H_2 \leftrightarrow C_nH_{2n+2} + nH_2O \quad (8)$$

$$nCO + 2nH_2 \leftrightarrow C_nH_{2n} + nH_2O \quad (9)$$

Fischer–Tropsch processes have been used since the 1920s, notably in Germany during WWII and also in South Africa during the Apartheid era, although reactor design and catalyst choice have been refined in recent years [36]. Iron and cobalt are typically selected as catalysts for current commercial FT operations [36].

Product yield and composition vary depending on the process conditions. The yields used in this study are taken from the literature. Petrol and diesel production via gasification and FT synthesis is assumed 5.17%wt and 7.79%wt of the initial biomass feed, respectively [28].

Bio-oil steam reforming

Approximately 60–80%wt of bio-oil is soluble in water [37]. This aqueous fraction can be steam reformed to produce hydrogen in a similar process used to steam reform methane [38]. However, reforming the aqueous fraction of bio-oil is presented with various challenges, most of which are related to coke formation on the surface of catalysts. Adding a solvent, such as methanol, can alleviate these issues, and typically a 10% methanol blend is prepared before reforming [20].

Steam reforming of bio-oil has only been demonstrated at laboratory scales (e.g. Refs. [39–41]), although a recent study provided a techno-economic model of a large scale facility [20]. The maximum stoichiometric yield of hydrogen that can be produced from steam reforming of bio-oil is 17.2%wt [42]. Steam reforming of a bio-oil methanol blend (10%) yields approximately 14.7%wt hydrogen [20].

Bio-oil upgrading

Bio-oil can be upgraded to produce petrol and diesel. This process consists of three steps: hydrotreating, hydrocracking and distillation (Fig. 2) [43]. Hydrotreating removes oxygen

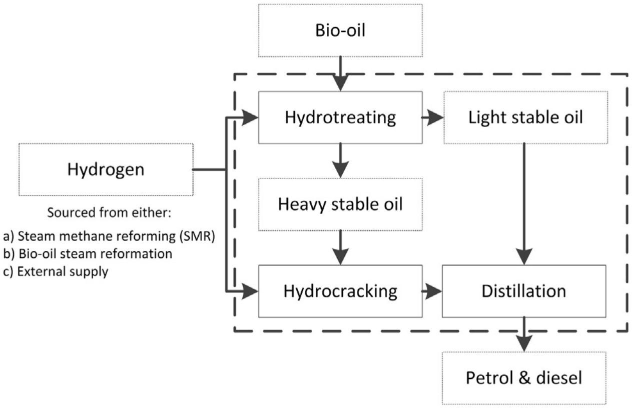

Fig. 2 – Bio-oil upgrading process.

from the compounds in the bio-oil mixture, which is followed by hydrocracking long chain hydrocarbons into shorter chain molecules. The products are distilled into petrol and diesel fractions.

Hydrogen is required for the hydrotreating and hydrocracking stages. Hydrogen may be delivered to an upgrading facility from an external source, or it may be produced on-site by steam reforming of natural gas or by steam reforming a fraction of the initial bio-oil feed. Upgrading bio-oil to petrol and diesel has only been demonstrated at the laboratory or small engineering development scale, but a recent study performed a techno-economic analysis of a commercial scale facility [43]. Yields of petrol and diesel from upgrading are approximately 31.35 and 1.65%wt of the bio-oil feed, respectively [43].

Materials and methods

This study investigates the production of hydrogen or synthetic petrol and diesel fuels using either woodchip, bio-oil, bio-slurry or torrefied wood feedstock derived from a mobile pyrolysis facility network using a forest residue resource. A model is constructed to analyse the technical and financial aspects of each fuel production pathway, and considers two point-of-delivery scenarios. The model is constructed in Matlab, and is based upon the volume of forest residues that are available for harvest. The model calculates: the quantity of mobile facility products available as feedstock for bio-fuel facilities; travel distances required (including total truck distances based on volume or weight capacities of trucks); feedstock storage requirements; size of bio-fuel facilities based on harvest volume, and; annual quantities of bio-fuels produced. Costs associated with each step of forest residue harvest and bio-fuel production are considered and a levelised cost of bio-fuel is calculated.

Point-of-delivery scenarios

Two point-of-delivery scenarios are considered in this study (Fig. 3). In scenario A, feedstock is delivered to a bio-fuel facility located at the centre of a biomass harvest region. This scenario models a situation where a bio-fuel facility is located within the forested region. In scenario B, feedstock is delivered to a bio-fuel facility outside of the harvest region, requiring greater transport distances.

Feedstock delivery

Harvesting forest residues includes the purchase, piling and chipping of forest residues into chip trucks at logging sites. Not all forest residues are available for harvest, and the spatial density of available forest residues assumed in this analysis is 65 m^3 km^{-2} [9]. Chip trucks transport the woodchips either directly to the bio-fuel facility or to the nearest mobile facility, depending on the delivery pathway selected. When mobile facilities are implemented the model calculates the amount of products available for transport as feedstock for a bio-fuel facility. Transport distances for woodchips and mobile facility products are generated and a levelised cost of feedstock delivered to the bio-fuel facility is calculated. Details of the methods used for modelling forest residue collection, mobile facility use and transportation of feedstock can be found in Brown et al. (2013) [9].

Bio-fuel facilities

Feedstock handling and storage

The type of storage employed at a bio-fuel facility depends on the feedstock characteristics, available storage space and the capital available for storage facilities. Green woodchips tend to be stored in large open uncovered piles on top of a base of concrete pads. Bio-oil and bio-slurry are stored in stainless steel tanks [8], and methanol is added to bio-oil to prevent ageing during longer term storage (10%wt) [20]. Torrefied wood is stored in open uncovered piles similar to green woodchips.

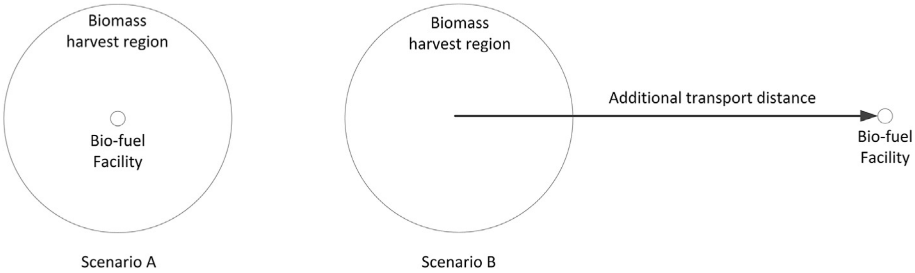

Fig. 3 – Point-of-delivery scenarios.

The model calculates two week reserve storage requirements at central facilities. For liquid storage at central facilities, the number of stainless steel tanks required is calculated based upon multiple instalments of 9400 m^3 capacity stainless steel tanks [8].

Pre-treatment

Green woodchips and torrefied wood need to undergo pre-treatment processes before being input to gasification reactors. Green woodchips are screened to remove metal, stone and dirt, before being dried and ground down to finer particles [44]. Torrefied wood only needs to be ground to finer particles. The model does not include an in-depth representation of pre-treatment processes, such as evaluating energy requirements of each process, as these vary depending on the equipment used [45].

Sizing of bio-fuel facilities

Bio-fuel facilities are sized based on the amount of feedstock available for bio-fuel production processes. The mass of feedstock from forest residues (for a given annual harvest) will depend on mobile facility use and product selected for feedstock, as mobile facilities use a portion of their products to meet thermal and electrical demands of the processes [9]. Furthermore, the quantity of feedstock can change during storage or pre-treatment processes. The quantity and properties of bio-oil are altered when methanol is added, and the mass of woodchips is reduced after drying. Feedstock variation is outlined in Table 1.

Once the mass of annual feedstock, M, is calculated using the values in Table 1 for each harvest volume, the size (tonne per day) of the bio-fuel facility, S, is calculated using Equation (10):

$$S = \left(\frac{M}{\sigma}\right) \div 365 \tag{10}$$

where σ is the capacity factor of the bio-fuel facility. A capacity factor of 90% is used in this study.

Bio-fuel production

When hydrogen or synthetic petrol and diesel are produced via pathways using gasification processes, all feeds are assumed to be different forms of oven-dry woodchips (i.e. chemically, they approximate to oven-dry woodchips in elemental composition [16,33]) and so the same product yield ratios are used. This is because no conversion factors from bio-oil, bio-slurry or torrefied wood to bio-fuels via gasification and water gas shift or Fischer–Tropsch reactions have been identified in the literature. Hydrogen or petrol and diesel production yields from steam reforming or upgrading bio-oil, respectively, are available in the literature and are used in the model. All bio-fuel production ratios, f, are provided on a mass basis, and the annual quantity of bio-fuel produced, F, is calculated as:

$$F = fM \tag{11}$$

When petrol and diesel are produced, the quantity of each is calculated using the ratios provided earlier in the introductory sections for Fischer–Tropsch reactions and bio-oil upgrading. For steam reforming of bio-oil, M refers to mass of the aqueous fraction of bio-oil as feedstock. It should be noted that scaling constraints and adjustments on the performance of bio-fuel production processes (as bio-fuel facility sizes are varied) have been avoided in this analysis for simplicity.

Hydrogen requirements for upgrading bio-oil to petrol and diesel

Bio-oil upgrading yields petrol and diesel as products. Hydrogen is required for the process, which may be derived from steam methane reforming (SMR), steam reforming of a fraction of the bio-oil feed, or from an external hydrogen source.

The total annual combined mass of petrol and diesel produced from upgrading bio-oil is calculated using Equation (11). The annual mass of hydrogen required by the upgrading process, M_{H_2}, is calculated using Equation (12):

$$M_{H_2} = \gamma_{H_2} M_{BO} \tag{12}$$

where γ_{H_2} is the mass of hydrogen required per unit mass of bio-oil feed, and M_{BO} is the annual mass of bio-oil feedstock [43,46,47].

If SMR is selected as the method for producing hydrogen, the annual mass of methane consumed, M_{CH_4}, is calculated using Equation (13):

$$M_{CH_4} = \frac{M_{H_2}}{f_{SMR}} \tag{13}$$

Table 1 – Mass of feedstock and fuels produced from forest residues (50% moisture content) [9].

Feedstock	Mass (tonnes) and *energy content* (GJ) of feedstock produced from 1 m^3 of forest residues	Mass (tonnes) and *energy content* (GJ) of bio-fuel produced from 1 m^3 of forest residues for each fuel production pathway			
		Gasification and water gas shift	Gasification and FT synthesis	Bio-oil steam reforming	Bio-oil upgrading[a]
Oven-dry woodchips	0.383	0.029	0.050	–	–
	6.889	3.444	2.102		
Bio-oil (with 10%wt methanol blend)	0.210	0.016	0.027	0.031	0.069
	3.486	1.892	1.155	3.037	3.009
Bio-slurry (with 20%wt char loading)	0.239	0.018	0.031	–	–
	4.489	2.150	1.312		
Torrefied wood	0.260	0.020	0.034	–	–
	5.970	2.342	1.430		

[a] Values provided are for bio-oil upgrading using an external source of hydrogen (not from bio-oil steam reforming).

where f_{SMR} is the ratio of hydrogen production from natural gas. The annual methane consumption is used to size the SMR facility at the bio-oil upgrading facility.

If a portion of the bio-oil feed is used to produce hydrogen for upgrading, the fraction of bio-oil feed to be steam reformed, $\gamma_{BO,SR}$, is calculated using Equation (14):

$$\gamma_{BO,SR} = \frac{\gamma_{H_2}}{\gamma_{H_2} + m_{ws} f_{SR}} \tag{14}$$

where m_{ws} is the percentage of bio-oil that is water soluble and f_{SR} is the mass ratio of hydrogen production from steam reforming of the aqueous fraction of bio-oil. The annual mass fractions of bio-oil to be either upgraded or steam reformed are then calculated, and two combined facilities (bio-oil upgrading and bio-oil steam reforming) are sized using Equation (10).

No production processes or storage capacities are assumed if hydrogen is sourced externally. Instead, the hydrogen is provided at a cost per kilogram.

Costs

Costs associated with feedstock collection and delivery to the bio-fuel facility are detailed in Brown et al. (2013) [9], and are not described here. The costs discussed in this section are those related to bio-fuel facilities only.

Woodchip and torrefied wood are assumed to be stored in open-air piles [44,48]. The annual cost of this storage method for commodity i (woodchip or torrefied wood), $C_{pile,i}$, is calculated using Equation (15):

$$C_{pile,i} = c_{pile} V_i \tag{15}$$

where c_{pile} is the cost per tonne to store commodity i, and V_i is the annual volume of commodity processed by the bio-fuel facility [48]. Bio-oil and bio-slurry are stored in stainless steel tanks. The capital cost of the storage equipment is calculated based on the number of tanks installed, and operation and maintenance charges are calculated accordingly. When bio-oil is used as feedstock, the cost of methanol is calculated based on a 10%wt blend with bio-oil.

Feed preparation for woodchips consists of screening for metals and other impurities, drying and grinding. Feed preparation for torrefied wood only requires grinding. The costs associated with these processes are considered additional capital costs due to the additional equipment required at the bio-fuel facility (Table 2) [28,29]. This equipment is not required for liquid feedstock, and therefore these additional costs are not included when bio-oil or bio-slurry feedstock are used. The pre-treatment capital cost is scaled appropriately for the size of bio-fuel facility and is added to the bio-fuel facility capital cost.

Table 2 – Data input for bio-fuel facilities and bio-fuel production.

Data	Value	Unit	Reference(s)
Gasification and Fischer–Tropsch facility			
Reference size	2000	ODTPD	[28]
Reference cost	269.02	$million	[28]
Operation and maintenance	6	%	[28]
Bio-fuel production	12.96	%wt feed	[28]
Production ratio (petrol/diesel)	0.4	–	[28]
Gasification and water gas shift facility			
Reference size	2000	ODTPD	[27]
Reference cost	255.15	$million	[27]
Operation and maintenance	6	%	[28]
Bio-fuel production	7.5	%wt feed	[27]
Feed preparation equipment			
Open-air pile storage	1.31	$ m^{-3}	[48]
Screening (2000 TPD facility)	1.90	$million	[49]
Rotary dryer (2000 TPD facility)	9.43	$million	[49]
Grinding (2000 TPD facility)	12.10	$million	[49]
Upgrading bio-oil facility			
Reference size	1500	TPD	[43]
Reference cost	138.34	$million	[43]
Operation and maintenance	2	%	[43]
Bio-fuel production	33	%wt feed	[43]
Production ratio (petrol/diesel)	0.95	–	[43]
Hydrogen requirement	5	%wt bio-oil	[43,46,47]
SMR facility reference size	74,400	kg_{CH_4} day^{-1}	[43]
SMR facility reference cost	95.94	$million	[43]
SMR facility operation and maintenance	2	%	[43]
SMR hydrogen production	0.44	$\%wt_{CH_4}$	[43]
Steam reforming of bio-oil facility			
Reference size	1198	TPD	[20]
Reference cost	155.00	$million	[20]
Operation and maintenance	4	%	–
Bio-fuel production	14.7	%wt bio-oil[a]	[20]
Methanol added to bio-oil	10	%wt bio-oil	[20]
Fuels and chemicals			
Density diesel	856	kg m^{-3}	[50]
Density petrol	737	kg m^{-3}	[50]
Density methanol	791.3	kg m^{-3}	[51]
Density bio-oil/methanol blend (10%wt methanol)	1040	kg m^{-3}	[52]
LHV diesel	41.66	MJ kg^{-1}	[50]
LHV petrol	43.47	MJ kg^{-1}	[50]
LHV hydrogen	120	MJ kg^{-1}	[50]
LHV methane	47.79	MJ kg^{-1}	[50]
Cost of methanol	0.53	$ kg^{-1}	[53]
Cost of natural gas	5.24	$ GJ^{-1}	[54]

[a] Aqueous fraction of bio-oil. Data for collection of forest residues and mobile facilities can be found in Ref. [9]. All costs are provided in 2013 Canadian dollars.

The capital cost of bio-fuel facility j utilising commodity i as feedstock, $C_{cap,i,j}$, is calculated using Equation (16):

$$C_{cap,i,j} = c_{ref,j} \left(\frac{S_{i,j}}{s_{ref,j}} \right)^{\kappa} \tag{16}$$

where $c_{ref,j}$ is the cost of a bio-fuel facility of reference size $s_{ref,j}$ (tonne per day), and κ is the cost scaling factor. If woodchip or torrefied wood is used as a feedstock, the reference capital cost includes feed preparation equipment. These additional costs are added to the reference capital cost of the bio-fuel facility and are, therefore, subject to operation and maintenance costs [28]. Equation (16) is also used to calculate the capital cost of SMR facilities (when hydrogen is produced from methane at a bio-oil upgrading facility), except that annual methane consumption is input rather than annual feedstock requirements. When upgrading uses hydrogen sourced from bio-oil steam reforming, Equation (16) is used to calculate the capital cost of both an upgrading facility and steam reforming facility separately. These costs are combined to produce a total capital cost (no cost savings other than labour are assumed through co-location of facilities).

The fixed operation and maintenance cost of bio-fuel facility j utilising commodity feedstock i, $C_{O\&M,i,j}$, is calculated using Equation (17):

$$C_{O\&M,i,j} = o_j C_{cap,i,j} \tag{17}$$

where o_j is an operation and maintenance fraction of capital expenditure (Table 2). Additional operating costs that are calculated by the model include those related to the purchase of methane or hydrogen when upgrading bio-oil. The annual cost of each is calculated using the values in Table 2.

The labour costs for bio-fuel facilities are based on the size of the bio-fuel facility. For a bio-fuel facility size of 2000 tonnes per day (TPD), fifty operating and four administrative staff with an hourly wage of \$40 and \$64, respectively, is assumed. The number of administrative workers is assumed constant for all plant sizes. For every increase or decrease in size of bio-fuel facility by 500 TPD, five additional or fewer operating workers are required [28].

Levelised cost of bio-fuel production

For each bio-fuel production route (Fig. 1), all costs spanning the operation lifetime of harvesting forest residues and producing bio-fuels are brought to present day value, totaled, and annuitized. These costs include all those calculated for the harvest and delivery of feedstock. The levelised cost of producing bio-fuel k from commodity feedstock i at bio-fuel production facility j in terms of energy (GJ), $LCB_{GJ,i,j,k}$, is calculated using Equation (18):

$$LCB_{GJ,i,j,k} = \frac{CRF \times NPV_{i,j,k}}{F_{GJ,i,j,k}} \tag{18}$$

where CRF is the capital recovery factor, $NPV_{i,j,k}$ is the net present value of all costs expended to deliver commodity i to bio-fuel facility j and produce bio-fuel k, and $F_{GJ,i,j,k}$ is the total energy content (GJ) of bio-fuel k produced from commodity feedstock i at bio-fuel production facility j.

The levelised cost of producing bio-fuels can be calculated in terms of energy content, volume or mass of the final fuels. To provide comparison between bio-fuel production routes in later discussion, the levelised cost of bio-fuel production is expressed either in dollars per GJ, dollars per litre, or dollars per kilogram of fuel.

Analysis performed

The model is used to determine the levelised cost of producing hydrogen or synthetic petrol and diesel fuels using each of the fuel production routes detailed in Fig. 1.

Initially, a base analysis is performed for delivery to a bio-fuel facility within a forested region (scenario A). The annual harvest for the base analysis is 1.717 million m^3, equivalent to delivering 2000 oven-dry tonnes per day (ODTPD) woodchips, and is a standard base size of bio-fuel facilities used in the literature. The spatial density of forest residues assumed for the base analysis is 65 m^3 km^{-2}, which is consistent with temperate forest data used in other studies (e.g. Ref. [28]). The base analysis therefore considers a harvest region of 528,307 km^2 over a 20 year harvest operation. The forest residues are modelled with an initial moisture content of 50%, and an oven-dry wood bulk density and LHV of 500 kg m^{-3} and 18 MJ kg^{-1}, respectively. All bio-fuel facilities are 'built overnight' and are 100% equity funded.

Subsequent analysis looks in more detail at: optimal harvest volumes for bio-fuel production from forest residues when using mobile facilities to harvest forest residues; additional transport distances to bio-fuel facilities (scenario B); and the effect of hydrogen source and purchase price when upgrading bio-oil to produce petrol and diesel.

Results and discussion

Base analysis

Results for levelised cost of bio-fuel (LCB) for the base analysis are shown in Fig. 4, which details the breakdown of costs related to forest residue collection, mobile facility use, transport of feedstock commodities, bio-fuel facility expenses and, when upgrading bio-oil, hydrogen production costs. Cost reductions for transport are apparent when using mobile facilities, yet purchasing and operating mobile facilities incurs costs that offset these savings. Thus, the net present value of all costs expended for each bio-fuel production route is similar, between \$1.0–1.3 billion (Fig. 4(a)). However, when the quantity or energy content of bio-fuels produced from each process is taken into account, the results for LCB vary significantly (Fig. 4(b)).

Hydrogen produced via gasification and water gas shift (WGS) of woodchip feedstock provides the lowest LCB of all bio-fuel production routes (Fig. 4(b)). Hydrogen production via gasification and WGS for other feedstock types is more expensive due to reduced quantities of feedstock available from mobile facilities for bio-fuel production. The LCB from gasification and WGS is 25.06 \$ GJ^{-1} (3.01 \$ kg^{-1}), 40.21 \$ GJ^{-1} (4.83 \$ kg^{-1}), 36.45 \$ GJ^{-1} (4.37 \$ kg^{-1}) and 31.81 \$ GJ^{-1} (3.82 \$ kg^{-1}) for woodchip, bio-oil, bio-slurry and torrefied wood feedstock, respectively. Hydrogen production via steam reforming of bio-oil is competitive with gasification and WGS processes, and has an LCB of 27.42 GJ^{-1} (3.29 \$ kg^{-1}).

Petrol and diesel fuels produced via gasification and Fischer–Tropsch (FT) synthesis are most expensive, for any feedstock. The variation between FT bio-fuel production costs using different feedstock is, again, due to the quantity of each feedstock delivered to the bio-fuel facility for a given harvest. The LCB from FT synthesis is 41.75 \$ GJ^{-1} (1.42 \$ $litre^{-1}$), 66.76 \$ GJ^{-1} (2.28 \$ $litre^{-1}$), 60.54 \$ GJ^{-1} (2.06 \$ $litre^{-1}$) and 52.92 \$ GJ^{-1} (1.80 \$ $litre^{-1}$) for woodchip, bio-oil, bio-slurry and torrefied wood feedstock, respectively.

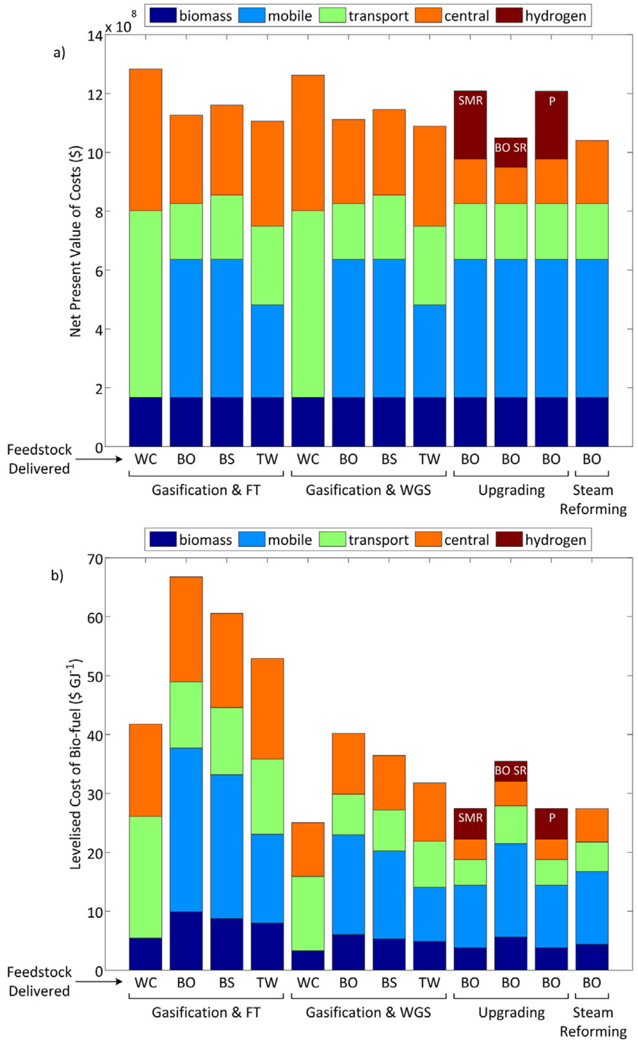

Fig. 4 – (a) Net present value of costs for all bio-fuel production routes (base analysis). (b) Levelised cost of bio-fuel for all bio-fuel production routes (base analysis). [Scenario A; base harvest (1.717 million m^3); WC: woodchip; BO: bio-oil; BS: bio-slurry; TW: torrefied Wood; SMR: steam methane reforming; BO SR: bio-oil steam reforming; P: purchased hydrogen (\$1.5 kg^{-1})]. The costs of bio-fuel production are divided into five categories: biomass (all costs related to purchase, piling and chipping of forest residues); mobile (all costs related to purchase, operation and labour requirements of mobile facilities, including on-site storage); transport (all costs related to transport of woodchips and mobile facility commodities); central (all costs related to purchase, operation, and labour requirements of the bio-fuel facility, including on-site storage); hydrogen (all costs related to production or purchase of hydrogen necessary for the bio-oil upgrading process).

Upgrading bio-oil to produce petrol and diesel yields a lower LCB than FT bio-fuels, regardless of the source of hydrogen required for upgrading. Upgrading bio-oil using hydrogen produced by steam reforming a fraction of the bio-oil feed requires less overall expenditures (Fig. 4(a)), but less petrol and diesel fuels are produced resulting in a higher LCB compared to other hydrogen sources for bio-oil upgrading (Fig. 4(b)). The LCB from bio-oil upgrading is 27.48 \$ GJ^{-1} (0.88 \$ litre^{-1}), 35.46 \$ GJ^{-1} (1.14 \$ litre^{-1}) and 27.46 \$ GJ^{-1} (0.88 \$ litre^{-1}) when using hydrogen sourced from SMR, bio-oil steam reforming and purchased hydrogen (1.5 \$ kg^{-1}), respectively.

Optimum harvest volumes

Fig. 5 shows how the levelised cost of bio-fuel (LCB) for hydrogen varies with the annual harvest volume of available forest residues. LCB results all follow the same trend: for small annual harvest volumes the LCB is high because there are large expenditures for the bio-fuel facility, yet the quantity of fuel produced is small. For large annual harvest volumes the LCB is high because, although more fuel is produced and economies of scale reduce the cost of the bio-fuel facility (per tonne feed), transport costs are high due to harvesting forest residues over an increasingly large area. There is an optimum low cost of bio-fuel production between these two regions.

The minimum LCB of hydrogen produced from gasification and water gas shift (WGS) of a woodchip feedstock occurs for an annual harvest of 947,000 m^3 forest residues (equivalent to a 1100 ODTPD bio-fuel facility), and the LCB is 2.92 \$ kg^{-1}. Transport requirements are reduced for delivery pathways using mobile facilities, therefore minimum LCB results for bio-fuel facilities using bio-oil, bio-slurry or torrefied wood occur at larger annual harvest volumes (i.e. larger bio-fuel facilities). Optimum sizes of gasification and WGS facilities using either bio-oil, bio-slurry or torrefied wood feedstock occur for harvests of 4.01 million m^3 (2560 TPD), 3.42 million m^3 (2490 TPD), 2.84 million m^3 (2250 TPD), respectively. For hydrogen production via gasification and WGS, woodchip feedstock provides the lowest LCB. However, as haul costs increase, torrefied wood feedstock becomes the lowest cost option, for larger annual harvests.

Hydrogen production costs via steam reforming of bio-oil are competitive with those of gasification and WGS of a

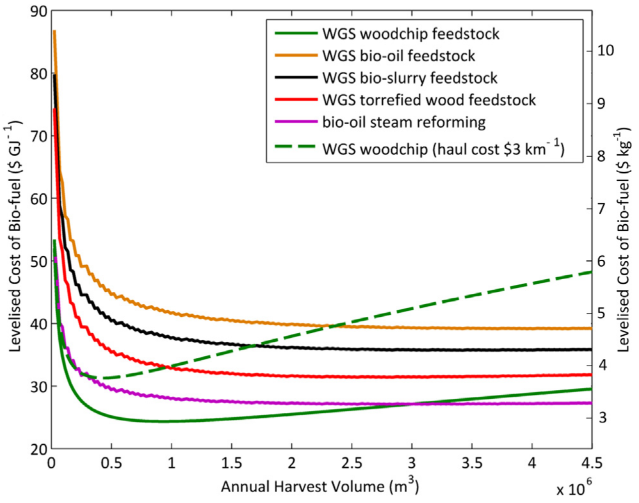

Fig. 5 – Levelised cost of hydrogen production for a range of annual harvest volumes.

woodchip feedstock. LCB results for steam reforming of bio-oil are less influenced by annual harvest volume, as mobile fast pyrolysis facilities reduce transport requirements of feedstock delivery. The minimum LCB occurs at an annual harvest of 2.84 million m^3 (1810 TPD), and the cost of hydrogen production is 3.25 \$ kg^{-1}.

Fig. 6 shows how the levelised cost of bio-fuel (LCB) for petrol and diesel fuels varies with the annual harvest volume of forest residues, for both Fischer–Tropsch (FT) and upgrading bio-fuel production routes. The minimum cost of FT bio-fuels produced from a woodchip feedstock occurs at an annual harvest of 992,000 m^3 forest residues (equivalent to a 1160 ODTPD bio-fuel facility), and the LCB is 1.39 \$ $litre^{-1}$.

Optimum sizes of FT facilities using either bio-oil, bio-slurry or torrefied wood feedstock occur for harvests of 4.30 million m^3 (2750 TPD), 3.71 million m^3 (2700 TPD), and 2.84 million m^3 (2250 TPD), respectively. For bio-fuel production via gasification and FT synthesis, woodchip feedstock provides the lowest LCB. However, if woodchip haul costs increase, torrefied wood feedstock becomes the lowest cost option, for larger annual harvests. For e.g. if haul costs of woodchips increases to 3 \$ km^{-1}, torrefied wood feedstock produces the lowest LCB results for annual harvests above approximately 1 million m^3, as shown in Fig. 6.

Bio-fuel production costs via bio-oil upgrading are lower than for bio-fuels produced via FT synthesis, and are less influenced by annual harvest volume because mobile fast pyrolysis facilities reduce transport requirements of bio-oil feedstock delivery. The minimum LCB occurs at 4.30 million m^3 (2750 TPD), 3.13 million m^3 (2000 TPD) and 1.96 million m^3 (1250 TPD) for bio-oil upgrading facilities using hydrogen sourced from SMR, bio-oil steam reforming and purchased hydrogen (1.5 \$ kg^{-1}), respectively. The minimum LCB for producing bio-fuels via upgrading is 0.86 \$ $litre^{-1}$ when using SMR for the hydrogen source.

The results of this analysis suggest optimally sized facilities are comparable in size with ethanol bio-refineries in North America (between 2000 and 3000 TPD) [7], although the amount of fuel produced by any pathway analysed in this study is but a fraction of the quantity produced by current fossil fuel facilities such as petroleum refineries or steam reforming natural gas. For instance, a 3000 TPD Fischer–Tropsch facility in this study produces approximately 293,000 L of petrol and diesel each day, whereas the average petroleum refinery in the U.S. produces 19.19 million litres each day [55].

Additional transport distances (scenario B)

Figs. 7 and 8 show how LCB results for hydrogen or synthetic petrol and diesel production, respectively, vary as the additional distance to the bio-fuel facility from the forested region increases from 0 to 500 km (scenario B). To compare minimum bio-fuel production costs for each bio-fuel production route, LCB results shown in Figs. 7 and 8 are for optimally sized bio-fuel facilities. The optimal size of bio-fuel facility for each bio-fuel production route does not change with additional transport distance because additional transport distances are independent of the annual harvest volume of forest residues.

For hydrogen production using gasification and WGS, woodchip feedstock produces the lowest cost hydrogen for distances up to 295 km. For larger distances, torrefied wood feedstock produces the lowest cost hydrogen. Steam reforming of bio-oil produces lowest LCB results of all hydrogen bio-fuel production routes for all additional transport distances above 85 km.

For a Fischer–Tropsch bio-fuel facility, woodchip feedstock produces the lowest cost bio-fuels for distances up to 290 km. For distances greater than 290 km, torrefied wood feedstock produces the lowest cost bio-fuels for a FT bio-fuel facility. Upgrading bio-oil provides the lowest LCB result of all petrol and diesel production routes for all additional transport distances. The final cost of bio-fuel does not increase substantially with distance because bio-oil transportation is inexpensive (compared to woodchip transport).

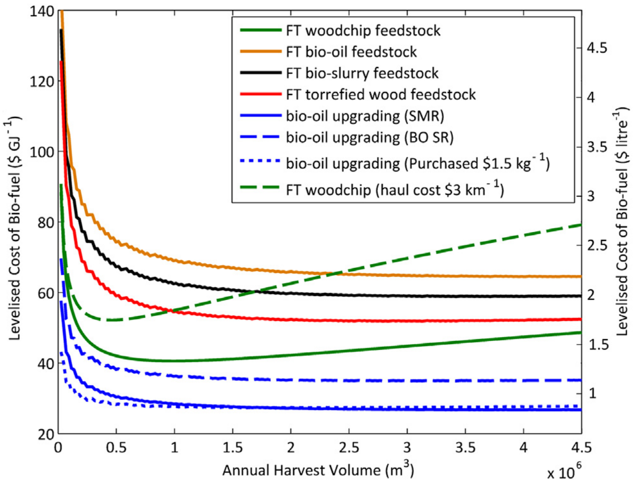

Fig. 6 – Levelised cost of bio-fuel (petrol and diesel) for a range of annual harvest volumes. Secondary y-axis is approximate.

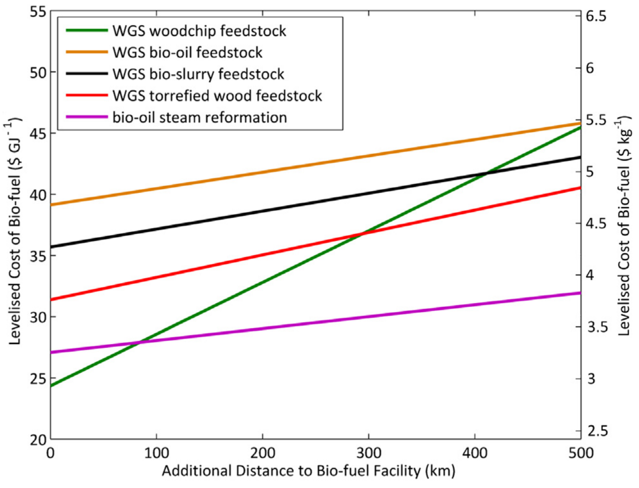

Fig. 7 – Levelised cost of bio-fuel (hydrogen) for optimally sized bio-fuel facilities when additional transport distances to a bio-fuel facility are required (scenario B).

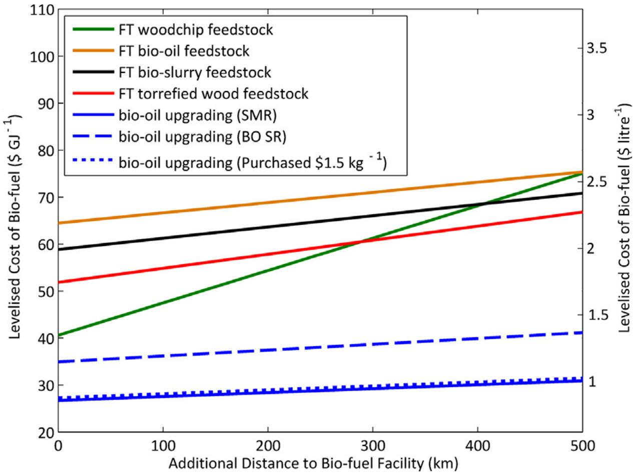

Fig. 8 – Levelised cost of bio-fuel (petrol and diesel) for optimally sized bio-fuel facilities when additional transport distances to a bio-fuel facility are required (scenario B). Secondary *y*-axis is approximate.

Hydrogen requirements for upgrading bio-oil

The cost of purchasing or producing hydrogen for upgrading bio-oil affects final bio-fuel production costs. Table 3 provides a range of LCB results as the purchase price of hydrogen is increased from 1.5 to 6 $ kg^{-1} (for an optimally sized bio-oil upgrading facility). If SMR is used to produce hydrogen from methane, the price of methane has little effect on LCB (a 50% change in methane price results in a 3.6% change in LCB). However, the capital and operating costs of an SMR facility play a larger role in dictating LCB results. Similarly, when hydrogen is sourced from a bio-oil steam reforming facility, the LCB of upgrading is influenced by the capital and operating costs of the steam reforming facility. However, LCB results for upgrading are most impacted by both the hydrogen requirement for upgrading bio-fuels and the hydrogen yield from steam reforming of bio-oil (when steam reforming bio-oil is used for the hydrogen source).

When hydrogen is produced from SMR or purchased, the quantity of petrol and diesel produced remains the same regardless of the hydrogen requirement for upgrading (although the size and cost of the SMR facility, or hydrogen purchase expenses, may change). If upgrading uses hydrogen sourced from the steam reforming of bio-oil, the hydrogen requirement of upgrading, and also the yield of bio-oil steam reforming, will both affect the quantity of petrol or diesel produced - the ratio of bio-oil sent to steam reforming or upgrading is changed. This, in turn, alters the final cost of petrol and diesel fuels produced (Fig. 9). Production costs are more sensitive to the hydrogen yield of bio-oil steam reforming, and the LCB can increase from 0.90 $ $litre^{-1}$ to 1.20 $ $litre^{-1}$ (for an optimally sized facility).

Table 3 – Levelised costs of bio-fuels via upgrading bio-oil using hydrogen purchased from an external source.

Hydrogen purchase price ($ kg^{-1})	LCB at optimum harvest ($ $litre^{-1}$)
1.5	0.88
3	1.05
4.5	1.22
6	1.39

Other considerations

The model presented in this study provides an analysis of producing hydrogen or synthetic petrol and diesel when using mobile facilities to harvest a general forest residue resource. However, biomass is a spatially and temporally dependent resource, and further considerations such as terrain, road networks and climate are necessary when examining particular geographic regions.

Bio-fuel production costs will also be influenced by local energy markets as discussed briefly in the section ‘Market demand and marginal costs’. Pairing mobile facility use with bio-fuel production on a large scale may not be practical for new operations, given that mobile facilities are currently not commercially available. Therefore, implementing mobile facilities on smaller scales is discussed in the section ‘Initiating use of mobile facilities’.

Market demand and marginal costs

The market demand, or competition, for forest residue resources may impact the quantity of resource available for bio-fuel production. As the demand for forest residues increases the purchase price of forest residues will likely increase, and industries that can harvest the resource for lowest costs will be in the best position to secure the resource. In this respect, competition for forest residues is generally not a concern of physical availability but instead an economic matter, in which demand change from one user can cause significant price changes for other users [56].

The marginal cost of using forest residue resources may reduce the extent to which the resource is utilised. The

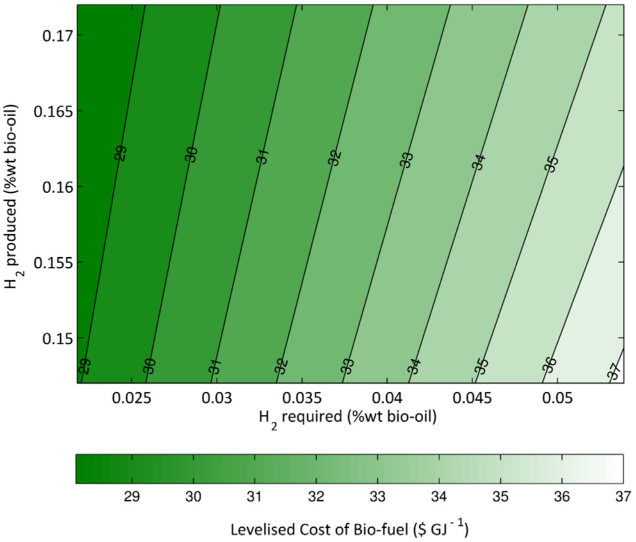

Fig. 9 – Levelised cost of bio-fuel (petrol and diesel) for ranges of hydrogen requirements for upgrading and hydrogen production from bio-oil steam reforming provided in the literature.

marginal cost of harvesting residues increases at a faster pace than the marginal cost of roundwood [57]. Therefore, harvesting large volumes of forest residues for large size bio-fuel facilities may not occur. Rather, supply may switch to roundwood when feedstock costs of roundwood are cheaper than that of forest residues. At this point, however, the bio-fuel sector starts to infringe on the supply of roundwood used by the logging industry and there is increased competition between industries.

On the other hand, mobile facilities reduce the marginal cost of a forest residue resource as they reduce transport requirements, which is an important factor of marginal costs [56]. Therefore, mobile facilities could allow greater penetration of forest residue resources that are largely unused due to high marginal costs [57].

Initiating use of mobile facilities

Since mobile facilities are not commercially available and are still subjects of research, it is unlikely that the first use of mobile facilities will be on a large scale, as the risk of purchasing multiple mobile facilities at one time to meet an entire harvest requirement of a bio-fuel facility is high. However, small numbers of mobile facilities do not provide lower delivered feedstock costs compared to conventional woodchip delivery [9], and, in addition, bio-fuel facilities using feedstock from mobile facility pathways produce lowest cost fuels when annual harvests are large (which would require many mobile facilities to meet harvest requirements). Thus, one question is whether a gradual introduction of mobile facilities can be economically viable without an incentive or policy driver.

For small scale implementation to be economically feasible, transport distances need to be large (over 250 km [9]). Therefore, mobile facilities would be most favourable for harnessing forest residue resources that are too far from facilities that would use such resources to justify conventional woodchip delivery. Mobile facilities may initially be suited to providing additional resources to existing infrastructure, such as power stations. If existing infrastructure can use mobile facilities products as feedstock without needing major changes to current operations, large capital costs for new bio-fuel facilities would be avoided. For instance, mobile facilities could produce either bio-slurry or torrefied wood to be co-fired with coal at existing power stations [16,19]. Over time, additional mobile facilities could be purchased to access greater volumes of forest residues and the destination of mobile facility commodities (bio-oil, bio-slurry, torrefied wood) may switch to a bio-fuel facility purpose-built to access feedstock from mobile facility delivery pathways.

Conclusion

The cost of producing hydrogen or synthetic petrol and diesel when using mobile distributed pyrolysis facilities to deliver a forest residue resource to a bio-fuel facility can be competitive with conventional bio-fuel production methods using gasification of a woodchip feedstock. Furthermore, minimum bio-fuel production costs occur at larger annual harvests of forest residues when using mobile facilities, as transport requirements are reduced.

Previous studies have shown that delivering bio-oil feedstock to a bio-fuel facility is the most expensive delivery option when implementing mobile facilities. However, this study shows that using a bio-oil feedstock in combination with bio-oil steam reforming or bio-oil upgrading facilities can produce hydrogen or petrol and diesel, respectively, at lower costs than bio-fuel production methods using gasification.

On an energy basis ($ GJ^{-1}), producing hydrogen is generally less expensive than producing synthetic petrol and diesel for bio-fuel production pathways that use mobile facility products as feedstock.

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